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Proposal and Investigation of a Method for Measuring Process Color Variation via Reflection Densitometer

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PROPOSAL AND INVESTIGATION OF A METHOD FOR MEASURING PROCESS COLOR VARIATION VIA REFLECTION DENSITOMETER

by

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MASTER'S THESIS

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ABSTRACT

This thesis proposes a method of using reflection density readings taken with a conventional graphic arts densitometer to provide a numeric measure of the visual difference between a sample press sheet and a reference sheet. This numerical measure was developed based on the theory that human response to variation in process color printing is more affected by changes in the proportions of process inks to each other than by variation in the overall inking level of the press sheet.

The thesis then goes on to explain how the proposed system was tested. First, a set of color samples was generated. Observer evaluations of these color samples were converted to numeric values using psychometric evaluation methods. Using statistical methods, observer evaluations in numeric form were then tested against values obtained by using the proposed system. Observer evaluations of the color samples were also compared statistically with values from the Total Color Difference system as an additional test.

The thesis concludes that the proposed system is a reliable predictor of observer response to color variation when the system is used for the purpose of comparing reference press sheets to sample press sheets.

CHAPTER I

INTRODUCTION

During the summer of 1978, I was an intern at the United States Government Printing Office (G.P.O.) in Washington, D.C. At that time the Quality Control Department of the G.P.O. was in the early stages of developing a quality attributes program for the purchase of printed products from the G.P.O.'s many suppliers. The basic thrust of the program was to assign acceptability limits to the many different attributes which make up a piece of printing. The department developed tolerances for almost every imaginable aspect of a printed piece, from the size and number of 'hickies' to acceptable durability standards for different types of bindings. All these acceptability standards were based on tests using simple, commonly available instruments for testing printed materials within the printing industry.

When we at the G.P.O. began to look for a simple method for assigning numerical acceptability limits to variation in process color printing, we found that a simple, reliable technique did not exist. We also found that there have been few attempts to develop process color variability tolerances for the buyer of printing. Ian White developer of the Print Quality Index for the Canadian government, avoided the matter entirely and set no tolerances on process color variation. We found that some very large publishers specify inks, paper, and the densities to which each process color should be run on standard color control bars which appear on the press sheet. For this approach to be effective, such publishers must have an employee remain at the printing plant during production of the printed piece to check that color bar densities are met throughout the run and to see that material specifications are met. This system of color control is expensive and is feasible only where there are enough resources to justify the expense.

Generally, the G.P.O., like other buyers, must inspect their printed products after finishing and binding, without the benefit of color bars. Even under ideal conditions, however, it is known that color control bars are not always an accurate indicator of color changes on other areas of the press sheet.[1] Furthermore, most buyers must procure printing from a variety of sources. Because printers use different ink sets, different presses, and different procedures, it is difficult to make up standard sets of specifications.

In addition to the approaches mentioned above, there is one notable approach to setting variability limits in process color printing. This method is explained in a paper by my thesis advisor, Irving Pobboravsky.[2] The paper describes a method for establishing variability limits in CIE space. Although the approach is not as complicated as using the CIE color identification system, it requires the use of a computer and would require many hours of work to implement. To put such a system into use, the G.P.O. would have to require any printer bidding on process color printing for the government to install such a system. Since the printing industry is made up of so many small shops, few companies would have the resources to comply with such a demand. This would severely limit the number of printers who could bid on process color work for the government.

Because of the difficulties of using available approaches for setting tolerances for process color variation, we at the Government Printing Office decided that it would be worthwhile to attempt to develop such a system. We decided that a system for measuring process color tolerances should have the following characteristics: 1. A numeric measure of color variation. 2. Color variation should be determined with conventional graphic arts instrumentation, readily available to printers doing process color work. 3. The measurement system should be easy to understand and put into effect. 4. The measurement system should allow color variation tolerances to be checked _after_ printing and binding. 5. The system should have acceptability limits which do not exceed the capacity of the printing process.

Hypothesis

This thesis is the result of my efforts to come up with such a system. Some of the preliminary work was done during my summer at the G.P.O., but the bulk of the development was done after I returned to R.I.T. As you shall see, the thesis proposes a method for using the conventional graphic arts densitometer as a basis for a numeric system for measuring color differences. Use of the conventional densitometer satisfies the first two system goals listed above (numeric measurement, and conventional instrumentation). The way the system is put into effect also satisfies the third and fourth system goals above (simplicity and checking tolerances after printing). However, the work presented in this thesis does not pretend to address the fifty requirement of the system, that of setting acceptability limits. This is not to say that acceptability limits cannot be developed, but only that they are beyond the scope of the thesis. The central question of the thesis is this: Can a conventional densitometer provide a numeric measure of the visual difference between a press sheet and an o.k. sheet which correlates with the visual difference as seen by observers?

Explanation of Proposed System

The key to the proposed method is use of the conventional densitometer. Undoubtedly, some readers will be skeptical as to the feasibility of basing such a method on this instrument. Although the reflection densitometer has been widely used in the printing industry and has proved to be an important element of many quality control programs, it is also "one of the most misunderstood, misused, and abused instruments in the industry, and has made significant contributions to the absence of "quality control."[3] Because the densitometer has been abused so often, its use as a tool for color measurement has been frowned on by some experts.[4]

GATF points out in Research Progress Report number 90, that densitometric color measurement 'cannot be extended to become a universal color measurement system such as the CIE system.'[5] But the same report goes on to explain that the densitometer is useful when used to assign quantitative tolerances to quality acceptability limits which have been determined visually. It also points out that if a densitometer is correlated, it can be used for matching a proof to a press sheet.

The proposed color measurement technique uses the densitometer to indicate density changes based on reference densities, and not as a universal color measurement system. The principal advantages of using the densitometer for this system are that it is easy to use, it is widely available, and it will do the job.

Besides the use of the conventional densitometer, another feature of the proposed system which some readers might find controversial is the way the readings from the reflection densitometer are manipulated to determine the numeric value for establishing color variation. Instead of simply matching densities of readings taken through the four filters in a densitometer, this system synthesizes these readings based on the observation that experienced human observers are more sensitive to change in the proportional amounts of colorant of each process ink applied to the press sheet than the overall amount of each colorant. In other words, if there is a process color patch made up of 25% Cyan, 50% Magenta, and 25% Yellow, it is more important to maintain this proportional relationship to establish color control than ensuring that the overall densities of the color patch increase or decrease.[6] For the system proposed in this thesis, the concept described above is central to calculating the value which indicates the amount of color variation from an 'o.k.' sheet to a press sheet from a production run.

Although observers will accept greater variations in overall density of a process color sample if the proportional relationships of the process inks are retained, change in overall density from an 'o.k.' sheet to a sample press sheet is, nevertheless, significant. Therefore, change in overall density is also part of the formula used to calculate the degree of variation from an 'o.k.' sheet to a sample sheet in the proposed system.

As mentioned above, observers appear to be more sensitive to changes in the proportions of process ink densities making up a process color patch than to the overall density of the patch. Not only are observers more sensitive to this type of variation, but also this type of variation is more likely to occur in process color printing. Consider that process color printing is produced by printing combinations of process inks beside and on top of each other to produce different colors via the halftone process. Each time a process ink is applied to a press sheet, the sheet must pass through a printing unit. When printing, the probability of a single unit going out of control is much greater than all the units reacting the same way at the same time. Therefore, the type of variation which the human eye is the most sensitive to, is the most likely to occur.

For example, let's suppose we have a green patch created by the halftone technique using two process ink densities as follows: cyan: 0.22, yellow: 0.25. And let's also assume we have two samples for comparison. The first sample has these densities: cyan: 0.32, yellow: 0.32. The second sample has these densities: cyan: 0.22, yellow: 0.32. The first of these two samples will appear much closer to the original because the proportions of the two remained much the same.

Retaining similar proportions of process ink densities appears to be more important in producing a close color match than maintaining absolute densities. The importance of this proportional relationship is the key to the system which I have developed for expressing color variation numerically. Variations in the proportions of process ink densities for the proposed system (to be called the Densitometric Color Value System, or ΔD) is calculated by first establishing the ratios of the process ink densities in a given sample area on the 'o.k.' or reference press sheet. The ratios are then calculated for the sample sheet. Any change in the ratio from the reference sheet to the sample sheet is a numeric value representing a color change in the overprint sample. I have named this numeric value Proportional Density Shift (PDS). The technique for calculating PDS is explained below:

Proportional Density Shift (PDS) is calculated by comparing density ratios from an area of the 'o.k.' press sheet. The following three steps determine these ratios:

1. Measure the red, green, and blue densities (D_r, D_g, D_b) of the 'o.k.' press sheet and the sample.

2. Sum each of these two sets of densities: (Note from this point, primed values represent the 'o.k.' press sheet and unprimed values represent the sample.)

Equation 1.1

$$\sum{}' = D_r{}' + D_g{}' + D_b{}'$$

Equation 1.2

$$\sum = D_r + D_g + D_b$$

3. Calculate the ratio of each density measurement to its sum and convert these ratios to percentages.

Procedure 2.1

$$\frac{D_r{}'}{\sum{}'} \cdot 100, \frac{D_g{}'}{\sum{}'} \cdot 100, \frac{D_b{}'}{\sum{}'} \cdot 100$$

Procedure 2.2

$$\frac{D_r}{\sum} \cdot 100, \frac{D_g}{\sum} \cdot 100, \frac{D_b}{\sum} \cdot 100$$

4. Calculate the absolute difference between the percent density for the 'o.k.' press sheet and the reproduction for each of the filter readings:

Equation 3.1: $\Delta D_r = |\% D_r{}' - \% D_r|$

Equation 3.2: $\Delta D_g = |\% D_g{}' - \% D_g|$

Equation 3.3: $\Delta D_b = |\% D_b{}' - \% D_b|$

5. Determine Proportional Density Shift (PDS) by adding the absolute values of the differences found in the previous step.

Equation 4.1: $PDS = |\Delta D_r| + |\Delta D_g| + |\Delta D_b|$

(Note: The amount of the difference between the respective ratios is of prime importance, not whether it is a negative or positive quantity. Because these differences are added together to determine PDS, they must be absolute values. If they are not absolute, the negative and positive differences could cancel each other leaving the incorrect impression of a much smaller PDS than actually exists.)

The use of ratios to develop PDS was also important because the human eye is more sensitive to changes in highlight density than shadow density. If ratios were not used, a system might have been developed which would have been applicable to a single density level only.

For example, to the human observer, the visual difference between two printed samples of densities 1.00 and 1.05 will appear to be much closer matches than two patches of densities .50 and .55. The visual difference will appear much greater in the lighter of the two samples. This is due to the fact that the human eye is more sensitive to density changes at lower printed densities. Since the human eye is, by definition, the standard for determining correct density changes in any measurement system, this fact must be included in any system measuring color variation. Because a small change in density level is a greater proportion of a highlight density than a shadow density, the effect is much greater.

For example, a change from .20 to .25 is a 20 per cent change in density while a change from 1.00 to 1.05 density is only a five percent change in density. These differing degrees of proportional severity reflect human response to different density levels as demonstrated by the Munsell Density tables.

The degree of sensitivity to different density levels in the human eye has been expressed quantitatively in the tables relating Munsell Value to density. The table below compares Munsell Density values at four different density levels with PDS values representing a .06 change in the density levels of one of the process colors. A comparison of the Munsell Values and the PDS values shows that the PDS values correlate reasonably well with human perception of equal density increments.

Table 1.1

A Comparison of Munsell Values and PDS Values at Various Density Levels

Density Level	Munsell Value	PDS Value
.25	7.92	9.30
1.00	3.51	2.70
1.50	1.94	1.73
2.00	.77	1.29

So far, we have concentrated on proportional change of process color samples. However, change in overall density must not be forgotten. If the proportions of the process inks making up a sample remain the same, but they increase or decrease markedly, the observer will notice color variation.

Therefore, the second part of the numeric value which makes up the Densitometric Color Value (ΔD) is change in the overall density of the color sample. This is referred to as Overall Density Shift (ODS) and is calculated as follows:

Overall Density Shift (ODS) is the absolute difference in the visual density between corresponding areas of the 'o.k.' and sample press sheets. To determine ODS, these steps are followed:

1. The densities of the 'o.k.' and sample press sheets are read:

   a. D_V'

   b. D_V

2. To find Overall Density Shift (ODS), calculate the absolute difference between the visual density readings of the 'o.k.' press sheet and the sample:

   Equation 5.1 $\quad ODS = | D_V' - D_V |$

The Densitometric Color Value (ΔD) is made up of the two component parts described previously: PDS or Proportional Density Shift and ODS or Overall Density Shift. Arriving at the Densitometric Color Value (ΔD) for any color is simply a matter of adding the PDS and ODS values together for the particular color sample being tested.

Equation 6.1 $\Delta D = PDS + ODS$

The following is a sample procedure for calculating the ΔD for a particular color: (A sample worksheet is included on the last page of the chapter to clarify the procedure.)

Part A. Proportional Density Shift (PDS)

1. Calibrate the densitometer to the manufacturer's standard. Then zero all four filters on the substrate.
2. Take density readings in the corresponding areas of the 'o.k.' press sheet and the reproduction. Record each reading in the appropriate column of the sample worksheet. (D_r, D_g, D_b and D_r', D_g', D_b').
3. Enter the density readings from Step 2 (above) in columns 1, 2, and 3 of the worksheet. Calculate the sums for these two sets of readings and enter them in column 4 of the worksheet.
4. Calculate the ratio of each density measurement to its respective sum and convert these ratios to percentages. (Procedure 2.1 and 2.2) Enter these percentages in columns 5, 6, and 7 of the worksheet.
5. Calculate the absolute difference between the percent density for the 'o.k.' press sheet and the reproduction for each of the filter readings. (Equations 3.1, 3.2, and 3.3) Enter these values

in the third row of the worksheet under columns 5, 6, and 7.

6. Determine Proportional Density Shift (PDS) by adding the absolute values of the differences found in the previous step. (Equation 4.1) Enter this value in column 8 of the worksheet.

Part B. Overall Density Shift (ODS)

1. Calibrate the densitometer to the manufacturer's standard. Then zero the visual filter on the substrate.
2. Take density readings in corresponding areas of the 'o.k.' press sheet and the reproduction with the visual filter. Record the two readings in the first column of the section headed Overall Density Shift.
3. Determine the absolute difference between the visual filter readings of the 'o.k.' press sheet and the sample. (Equation 5.1) Enter this value in the column headed ODS.

Part C. Densitometric Color Value (ΔD)

1. Determine the Densitometric Color Value (ΔD). (Equation 6.1)

Sample Worksheet

Part A. Proportional Density Shift

Col No.	1	2	3	4	5	6	7	8
	Dr	Dg	Db	Σ	$\frac{Dr}{\Sigma}\cdot 100$	$\frac{Dg}{\Sigma}\cdot 100$	$\frac{Db}{\Sigma}\cdot 100$	PDS
O.K. Sheet	.92	.76	.69	2.37	38.81	32.07	29.12	
Sample Sheet	.97	.80	.75	2.52	38.49	31.75	29.76	
ΔDx					.32	.32	.64	1.28

Part B. Overall Density Shift

Col No.	1	2
	DV	ODS
O.K. Sheet	.88	
Sample Sheet	.95	
ODS		.07

Part C. Densitometric Color Value (ΔD)

$\Delta D = 1.28 + .07 = 1.35$

$\Delta D = 1.35$

Notes to Chapter 1

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CHAPTER II

METHODOLOGY

Once the system described in the previous chapter had been developed, procedures to test the validity of the system needed to be developed. In order to test these procedures it was first important to recognize that 'color' is a subjective phenomenon— it is a human reaction to the range of electro-magnetic radiation from approximately 400 to 750 nanometers. The final judge of any color or color difference cannot be a machine, but must be a human or group of humans because color, by definition, is a human reaction to a physical phenomenon. It is this fact which has made specifying color by quantitative means difficult for those who have attempted it. It is also this fact which makes testing the system difficult. Because color is a sensation, no single system of quantifying color variation has proved to be an unassailable standard.

Because color is a subjective phenomenon, it was necessary that the system be tested both by comparisons with observations by humans under proper test conditions, and by comparison with another commonly accepted numerical system for quantifying color differences. The key to testing the system was to develop a test method for converting human responses to specific samples to quantitative data which could then be compared with the Densitometric Color Values (ΔD) from the proposed system.

Fortunately, such methods for quantifying human responses to subjective phenomenon are used regularly in the field of psychology. These methods of quantifying human responses are known as psychometric evaluation techniques.

Several techniques were evaluated before finding the most appropriate. Among those techniques evaluated was a simple rank-ordering or ordinal scaling of numbers. This technique was rejected as too crude since humans are capable of a high degree of color discrimination under the right conditions. Next, use of the interval scale was examined. One approach for developing an interval scale is the use of the pair comparison technique. However, this approach was ultimately rejected because of the very large number of observations needed. So many comparisons would be required that each observer would need to spend several hours examining the samples. Such a long time requirement to judge the samples would lead to inaccurate judgements due to boredom, and would have made it difficult to recruit observers.

Fortunately, an equally accurate, but much simpler and faster psychometric method is the graphic rating scale. To judge samples using this technique, observers indicate by graphic procedure the attribute intensity of two anchor stimuli. Another common graphic rating procedure, the one chosen for the experiment, uses only a single anchor stimulus and asks observers to locate samples on a straight line so that the distances between the samples are representative of the respective attribute distances between the samples. Verbal indicators are placed along the graphic line to help observers locate the samples where they see fit. A sample of such a graphic scale used for this experiment follows: (The actual graphic rating scale used for testing is reproduced in Appendix A.)

identical

close

similar

different

very different

Figure 2.1: Sample Graphic Rating Scale

The graphic rating scale is used by asking an observer to judge how closely a number of color samples approaches the color of a reference sample. For example, an observer would be given a reference sample and three other color samples labeled A, B, and C. He would then be instructed to indicate on the graphic scale where he felt each of the samples fell in relation to the reference sample. The observer, for example, might indicate the relationship of the three samples to the reference sample on the graphic rating scale like this:

A	→	identical
C	→	close
B	→	similar
		different
		very different

Figure 2.2: Sample Graphic Rating Scale in Use

Once the graphic rating of the three color samples is complete, converting these graphic relationships to quantitative values is a simple procedure as explained in Guilford's book, Psychometric Methods.[1] A numerical scale was placed next to the graphic scaling line and each sample was assigned the respective quantitative value on the scale. These numbers are then used as the quantitative equivalent of the observer's judgement for each sample. For example, in the graphic scale below, sample A would receive a value of 1, sample C would receive a value of 3, and sample B a value of 6.

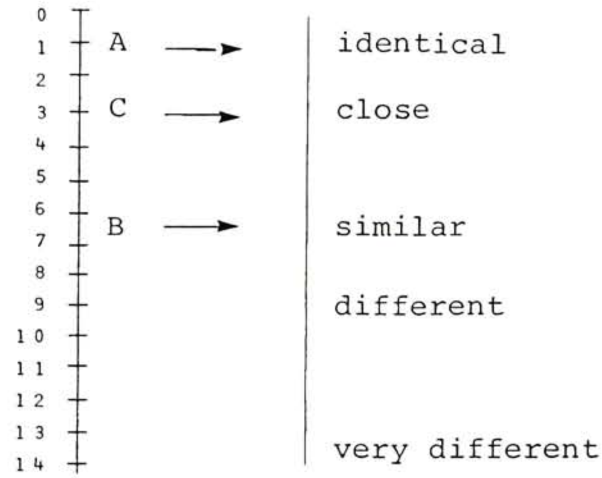

Figure 2.3: Conversion of Graphic Rating Scale Information to Numeric Values

The methodology for testing the hypothesis in this thesis is to compare human perception of the proposed system with values calculated using the Densitometric Comparison System. Once human perception of color samples are quantified using the graphic rating scale described above, values were calculated for the same samples using the Densitometric Comparison System as described in the first chapter. With numeric values for both human and machine response to the same color samples, the two systems were evaluated for agreement using statistical correlation techniques.

As an additional test, values for the same samples using the generally accepted Total Color Difference (ΔE) value were calculated. Total Color Difference (ΔE) is calculated by determining colorimetric densities and then converting these densities to tristimulus values. (The method for calculating Total Color Difference (ΔE) is explained in Appendix B.) The Total Color Difference (ΔE) for each of the color samples used for testing the Densitometric Comparison System was calculated. Then, statistical techniques were again used to compare Total Color Difference values with the observations of the observers.

In this way, the observations of human observers were tested against both the Densitometric Comparison System and against the more complex, but generally accepted Total Color Difference value.

Before explaining the testing procedure further, I will discuss how the color samples used for testing were generated. At the outset, a number of approaches for obtaining samples of color variation were considered. First, the possible use of pre-printed process color screen tints was evaluated. Such an approach would provide a high degree of control, but was rejected because judgement of any color is influenced by surrounding colors to such a degree that isolated screen tints would not reflect the conditions under which this system would be used. Also, collecting waste sheets from press runs to obtain samples of sufficient color variation to conduct an objective experiment was attempted. However, it was found that data from press sheets was not representative of the wide range of possible color variation in four-color printing.

Due to the problems mentioned above, a special press run was required for generating a full range of color variation sufficient for testing the hypothesis. Fortunately, press time was granted on the four-color Rockwell web press in the Graphic Arts Research Center.

Since a wide range of color samples for testing was needed, it was important to develop a careful plan for generating these samples. After consultation with Richard McAllen of G.A.R.C.,[2] as well as the pressmen at the Graphic Arts Research Center, I decided that the best approach to developing a full range of color samples was to start at the lowest density levels and build to a variety of higher aimpoint densities for each of the process colors. Starting with the lower densities and moving to higher densities made sense because an offset lithographic press naturally takes time to "come up to color", or to reach proper printing density.

To be sure the objectives of the press run were understood by all involved, a memo was distributed to the press crew two days before the press run was scheduled so that any questions could be answered. The memo explaining the press run's objectives and the desired aimpoint densities can be found in Appendix C.

The Graphic Arts Research Center had a variety of four-color negatives available to choose from for printing my test samples. I chose four images from a medium-quality fashion publication. (See samples of these printed images in Appendix D.) These four images were chosen because they might be found in a typical medium-quality four-color printing job. That is, there were no extraordinary procedures or demands in printing these images. Nor, were these images of low quality. Also, among these four images there is a wide range of color densities and overprints suitable for testing.

During the press run, the color control bars on the press sheet were monitored constantly, until each aimpoint density was recorded. After obtaining a sheet with the required aimpoint densities, the sheet was saved. After the press run, these sheets were examined as a group. Ten press sheets with a wide range of color variation in comparison with the 'o.k.' press sheet were chosen to serve as samples for testing.

After obtaining the color samples for testing, time was spent experimenting with the densitometer to discover the best way to take readings within the press sheet. As mentioned in Chapter I, one of the most important aspects of the Densitometric Color Value System (ΔD) is that it evaluates color within a press sheet without the use of color bars for taking densitometer readings. Therefore, the densitometer was used to take readings within the printed image. Because the collection area of the graphic arts densitometer is only about five millimeters in diameter, correct placement of the collection device was important in obtaining repeatable readings. After some informal testing, I found that very repeatable densitometer readings could be maintained when centering the collection area of the densitometer on a tiny dot or imperfection in the area to be tested. When using such a dot for a target, readings were very repeatable.

To test the observers judgements as planned, I needed to take readings with a densitometer to calculate the Densitometric Color Value (ΔD), and with a small-spot colorimeter to calculate the Total Color Difference value (ΔE). Therefore, a densitometer which could be converted from a densitometer to a small-spot colorimeter by simply changing the filter turret was used. Readings from the color samples were collected using the instrument first as a standard graphic arts densitometer, and then as a small-spot colorimeter. By using the same instrument for collecting data for both the Densitometric Color Value and for the Total Color Difference value, inter-instrument error was reduced. Before taking the readings, the instrument was fully cleaned and the filters were checked. Then readings were taken in each of the appointed areas using the instrument as both a densitometer and as a small-spot colorimeter.

After taking the readings, the Densitometric Color Values (ΔD) and the Total Color Difference value (ΔE) were calculated and recorded in their respective columns on the data collection sheet, a sample of which appears in

Appendix E. To expedite calculating the Densitometric Color values (ΔD), I wrote a program for my HP-25 calculator. A program the Graphic Arts Research Center had available was used for converting tristimulus values to the Total Color Difference value (ΔE).

Before continuing with the statistical analysis of the data, the human observers' rating of the data had to be completed. As explained earlier in this chapter, a graphic scaling technique was used to develop numeric values for observer evaluations of the color samples.

Nine people were chosen for the panel of observers. These observers all had familiarity with process color printing, from either a production or scientific orientation. It was expected that their familiarity with process color printing would give an accurate representation of a printing buyer's response to process color printing.

Before evaluating the color samples, each observer was given a set of general instructions describing the graphic scaling techniques and showing a sample of the graphic scaling rating sheet to be used.

The instructions encouraged the observers to use their own best judgement when evaluating the color samples, but to limit, as much as possible, their evaluation to the small areas to be read by the densitometer/small-spot colorimeter. After finishing the general instructions on the use of the graphic rating scale for the experiment, the observers were encouraged to ask questions.

After answering any questions, the observers were shown a sample printed sheet in which the areas to be evaluated were indicated. This sheet was known as the Evaluation Guide and was used only for the purpose of clearly locating the areas within the image which were under consideration. (Sample Evaluation Guides appear in Appendix D.) Each observer was then given a more detailed set of procedures describing how to go about judging the samples. These procedures follow:

1. Use the Evaluation Guide to locate the small areas to be judged. There is an Evaluation Guide Sheet for each different image.
2. Find what you consider to be the sample which most closely matches the reference color. Indicate where this sample most appropriately lies on the line by writing its identification letter beside the desired spot on the line and drawing an arrow to the desired spot. For example, if you felt that sample C were somewhere between close and similar to the reference sheet, you would place the letter C opposite that place in the column and draw an arrow.
3. Now, find what you consider to be the sample most unlike the reference color. Indicate where on

the continuum this sample should be placed and mark it as you did in Step 2.

4. Now, proceed to compare the remaining samples to the reference sheet and indicate the placement on the line you feel best describes their relations to the local colors in the reference press sheet. When making this decision, be sure to compare the small color area on the sample in question with the same area on the reference press sheet.

After reading the specific procedures and clarifying any unclear points, the observers began the ranking procedure. All samples were viewed in the same viewing booth under standard viewing conditions of 5000 degrees kelvin in order to standardize conditions. In an attempt to encourage the careful consideration of all samples by the observers, they were encouraged to break from the process of evaluating the samples as soon as they became bored or felt their minds wandering. Most observers took advantage of this chance to break from evaluating the samples. The average time for judging all the samples was an hour and fifteen minutes.

Once the graphic rating of the color samples was complete, conversion of these judgements to quantitative values was a simple procedure as explained in Psychometric Methods. As described earlier, a numerical scale was simply laid next to the graphic scaling line, and the samples were assigned the adjacent quantitative value on the scale. These numbers were then used as quantitative equivalents of the observers' judgement for each sample.

The form used to collect and organize the data for analysis appears in Appendix E. At the top of the form, the image and the area within the image to be evaluated are indicated. Running down the left hand side of the form are letters identifying the ten samples to be judged. Along the top, in the first nine columns are the initials of each of the observers. In the columns below the initials, the observers' judgements of the color samples are recorded. As explained previously, these quantitative values were extrapolated from judgements made on the graphic rating scale.

The tenth column, headed S, is the standard deviation of the observer evaluations for each of the samples. The standard deviation was calculated to explore the degree of observer agreement on the evaluation of the color samples.

The eleventh column, headed $\bar{X}$, is the arithmentic mean of the observer evaluations of the color samples. The arithmetic mean was used to produce a single value representing all the observer judgements of the samples.

In the final two columns, headed ΔE and ΔD, the respective ΔE (Total Color Difference) and ΔD (Densitometric Color Value) for each sample are recorded after they have been calculated using the formulas described earlier. After collecting the data and organizing it on these forms, the data was analyzed. The analysis and results are explained in the next section of the thesis.

Note to Chapter II

1. Guilford, J.P. Psychometric Methods. McGraw Hill Inc., New York, 1954, pp. 266-90.

2. G.A.R.C. (The Graphic Arts Research Center) has been renamed since I carried out the testing for this thesis. G.A.R.C. is now called The Technical and Education Center.

CHAPTER III

ANALYSIS AND DISCUSSION OF THE DATA

As mentioned in Chapter II, four different printed images were evaluated by the observers, by the ΔD System and by the Total Color Difference System (ΔE). Three areas were evaluated within each of these images for a total of twelve distinct color areas evaluated by the observers and the two 'objective' systems of measurement. As wide a variety of colors for evaluation as possible was chosen, including fleshtones and colors of varying hue, lightness, and saturation. The four printed images to be tested were identified by the Roman Numerals I, II, III, IV. Within each of these sample images the three areas to be evaluated were identified by the numbers 1, 2, and 3. These areas were identified only on the sample sheet known as the Evaluation Guide. Samples of the Evaluation Guides with the areas to be evaluated identified appear in Appendix D.

For each of the areas evaluated, the observers judgements were tested for degree of agreement between both the corresponding Densitometric Color Value (ΔD) and the Total Color Difference value (ΔE) using the correlation coefficient (r). (The correlation coefficient is defined in

Appendix F.) The forms containing the collected and tabulated data, including the observers' numeric value, the ΔE, and ΔD values for each color sample are presented in Appendix G.

The following table presents the correlation coefficients expressing the degree of agreement between observers' judgements and the two quantitative systems for each of the color locations tested:

Table 3.1

A Comparison of $r_{\Delta D}$ and $T_{\Delta D}$ Values for Test Samples

Image No.	Test Location	Color Description	$r_{\Delta E}$	$r_{\Delta D}$
I	1	brownish/yellow	.74	.86
I	2	bluish/neutral	.35	.77
I	3	blue	.90	.92
II	1	light purple	.82	.88
II	2	dark purple	.51	.87
II	3	flesh tone	.77	.87
III	1	dark green	.93	.77
III	2	orange	.86	.92
III	3	light green	.71	.94
IV	1	red	.97	.86
IV	2	brown	.88	.74
IV	3	flesh tone	.78	.71

Examination of the correlation coefficients comparing observer numeric judgements and both the ΔE and ΔD systems indicates statistically significant agreement for most samples. For any given sample, the Total Color Difference (ΔE) or the Densitometric Color Value (ΔD) may have greater agreement with observer judgements but, on the whole, neither quantitative system has a predominately higher correlation at all levels. Most of the correlation coefficients for the two systems are significant to .10 and many are significant to .05. There are two exceptions to this pattern, however. The ΔE system shows little correlation between observer judgements on Image I, location 2 with only a .35 correlation coefficient. There also is little correlation between observer judgements and the ΔE system on Image II, location 2 with a .51 correlation coefficient. I cannot explain why these readings show so little agreement with observer judgements. However, it is interesting to note that both samples showing poor correlations are near-neutrals. Otherwise, I could find no pattern between the correlation coefficients and color description.

It should be pointed out that it is very surprising that a conventional densitometer produced a more accurate prediction of human color response than a colorimeter because the colorimeter is an instrument which has been specifically designed to match the color response of the standard observer. The purpose of this thesis, however, has not been to prove that the densitometer is superior to a colorimeter, but only that a densitometer could be used to provide a reasonably accurate prediction of color response under certain circumstances. The fact that the colorimeter did not perform as well as the densitometer on two of the samples tested may well be an abberation due to the particular group of observers. In any case, it is not presented as an important conclusion of the thesis, but only as a point worthy of comment. The use of the Total Color Difference Value (ΔE) to test the Densitometric Color Value (ΔD) was not meant to prove that the Densitometric Color Value (ΔD) is somehow superior, but only to use a commonly accepted means of color measurement as an additional test of the hypothesis.

The statistical analysis of the two systems indicates that the Densitometric Color Value (ΔD) appears to be a reliable indicator of human response to process color printing color variation when examined under standard viewing conditions and provided that it is used under conditions for which it was designed.

However, although the system has made a first step in proving itself statistically, it is certainly not an infallible method for predicting human response to color variation. Because perception of color is truly a subjective phenomenon, it may be that it is inappropriate to try to quantify response to color for the print buyer. Certainly, the print buyer will predominate in any disagreement about color since he is paying for the printed product.

The subjectivity of human response to the range of electromagnetic radiation which we call color can be seen by examining the standard deviations of observer numeric judgements on the data collection sheets for the various color samples (Appendix G). While there is a general pattern of consistency in the observer ratings of the samples, it can be seen that there are also wide swings of judgement by single individuals in comparison with other observers of the samples as indicated by the size of the standard deviations.

Before it can be said that the Densitometric Color Value System is sufficiently accurate and simple for field use, I would recommend field testing the system with a larger number of observers, some of whom should be print buyers. Also, a larger number of color samples using different images, ink sets and stocks is desirable. Assuming that the tests were successful and the buyers felt the system was workable, it would be necessary to develop acceptability limits for each of the various printing processes to be sure that the testing procedure would not exceed process capability.

CONCLUSIONS

1. Evaluation of the data contained in the previous chapter answers the hypothesis stated in Chapter I. A conventional densitometer can provide a numeric measure of the visual difference between a press sheet and an o.k. sheet which correlates well with the visual differences in color variation as perceived by a group of observers.

2. Since the Densitometric Color Value System appears to be easier to use and understand than other color measuring systems, it may be preferable when comparing o.k. press sheets to sample press sheets.

3. Human response to process color variation depends on both the amount of each ink applied to the substrate and the proportion of each process ink to the other amounts of process color. Therefore, it is advisable to approach control of the printing process, not by setting an arbitrary tolerance such as plus or minus 0.05, but by a system such as the Densitometric Color Value System which takes into account the effect of proportional density change on human perception of such changes.

Based on the above observation, attempts to control process variation through feedback from on-press densitometry might do well to use the Densitometric Color Value system as a basis for such control, instead of attempting to control variation to arbitrary levels such as density variations of plus or minus 0.05.

4. The Densitometric Color Comparison Value (ΔD) was a more reliable predictor of observer response to color variation than the Total Color Difference Value (ΔE) when both systems were used for the purpose of comparing o.k. press sheets to sample press sheets. For twelve color samples tested, the Densitometric Color Comparison Value (ΔD) had significant correlations with observer response of at least .10 for all samples. The Total Color Difference Value (ΔE) developed correlations significant to .10 in only ten of the twelve samples tested. The fact that the readings from the colorimeter (ΔE) did not perform is probably an aberration due to the makeup of the group of observers or faulty technique in taking the readings. In any case, this point is not presented as an important finding of the thesis, but as a point worthy of comment and further study.

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BIBLIOGRAPHY

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APPENDICES

APPENDIX A

SAMPLE GRAPHIC RATING SCALE

NAME ____________________ Press sheet name: ____________________

No. 1 ____

identical close similar different very different

No. 2 ____

identical close similar different very different

No. 3 ____

identical close similar different very different

APPENDIX B

MATHEMATICS FOR CONVERTING COLORIMETRIC DENSITIES TO Δ E VALUES

1. Convert colorimetric densities from small-spot colorimeter, D_r, D_g, D_b to colorimetric reflectances, R, G, B:

   $R = 10^{-Dr}$

   $G = 10^{-Dg}$

   $B = 10^{-Db}$

2. Transform* the set of colorimetric reflectances to tristimulus values, X, Y, Z (for Illuminant D_{5000}):

   $X = 1.3255R - 0.5629G + 0.2014B$

   $Y = 0.4957R + 0.4490G + 0.0052B$

   $Z = 0.8248B$

   *"Conversion of a Densitometer to a Colorimeter," Pearson, M. L., and Yule, J. A. C., TAGA Proceedings, 1970, p. 404.

3. Transform these tristimulus values to an approximately uniform color space called C.I.E.L.* a* b*. (In a truly uniform color space, the distance between any two colors is proportional to the perceived color difference):

$$L^* = 116\ (Y/Yo)^{1/3} - 16 \quad \text{where } Y/Yo > 0.01$$

$$a^* = 500\ [(X/Xo)^{1/3} - (Y/Yo)^{1/3}]$$

$$b^* = 200\ [(Y/Yo)^{1/3} - (Z/Zo)^{1/3}]$$

where: X_o, Y_o, Z_o are the tristimulus values of the illuminant. In this case, Illuminant D_{5000} was used, whose tristimulus values are:

$X_o = .96402$

$Y_o = 1.0$

$Z_o = .82436$

4. To obtain the Total Color Difference (ΔE) between a reference and a sample, obtain the L*, a*, b* for both the sample and the reference and perform the following calculation:

$$\Delta E = [(L_R - L_S)^2 + (a_R - a_S)^2 + (b_R - b_S)^2]^{1/2}$$

where: subscripts, R & S represent the reference and sample.

APPENDIX C

MEMO CONCERNING PRESSRUN OBJECTIVES

MEMO

SUBJECT: Press Run, Jan. 18, 1978 - Russ Harris' Thesis

TO: Richard McAllen, Irving Pobboravsky, GARC Press Crew

Thesis Objectives: To see if any ordinary densitometer can provide measurements of color reproductions which accurately agree with the color variation seen by observers. If the densitometer agrees with the way people see color variation, this will allow buyers of printing to give numerical specifications to printers.

Press-run Objectives:

1. To produce pictoral color prints which have as much variation as possible in:
   a. Hue
   b. Overall density

Materials Specifications:

1. Stock: Coated
2. Ink: One ink set

Samples needed:

Following you will find a list of 12 samples with aim point densities. These densities are approximate indicators only, and are meant to demonstrate the scope and type of variation needed. During the press run, other samples which fall between these approximate values will also be pulled.

SAMPLES NEEDED

1. Start all printers with low s.i.d., but o.k. color balance:

Cyan	Magenta	Yellow	Black
.70	.70	.40	1.00

2. Increase Cyan printer to 1.30; other printers remain same
3. Increase Cyan printer to 1.80
4. Decrease Cyan printer to 1.30; increase Magenta printer to 1.30
5. Increase Magenta printer to 1.80
6. Decrease Magenta printer to 1.30; increase Yellow printer to 1.00

   Note: This is the o.k. press sheet. Color balance should be correct and the solid ink densities on this sheet should read:

Cyan	Magenta	Yellow	Black
1.30	1.30	1.00	1.50

7. Decrease Cyan printer to .70; increase Yellow printer to 1.50

8. Decrease Yellow printer to 1.00; increase Cyan printer to 1.30; increase Black printer to 2.00
9. Increase Magenta printer to 1.30
10. Increase Cyan printer to 1.80; decrease Black printer to 1.50
11. Increase Magenta printer to 1.80
12. Increase Yellow printer to 1.60; increase Black printer to 2.00

S.I.D.

	Cyan	Magenta	Yellow	Black
1.	.70	.70	.40	1.00
2.	1.30	.70	.40	1.00
3.	1.80	.70	.40	1.00
4.	1.30	1.30	.40	1.00
5.	1.30	1.80	.40	1.00
6.	1.30	1.30	1.00	1.50
7.	.70	.70	1.50	1.50
8.	1.30	.70	1.00	2.00
9.	1.30	1.30	1.00	2.00
10.	1.80	1.30	1.00	1.50
11.	1.80	1.80	1.00	1.50
12.	1.80	1.80	1.60	2.00

APPENDIX D

SAMPLE PRESS SHEETS/
SAMPLE EVALUATION GUIDES

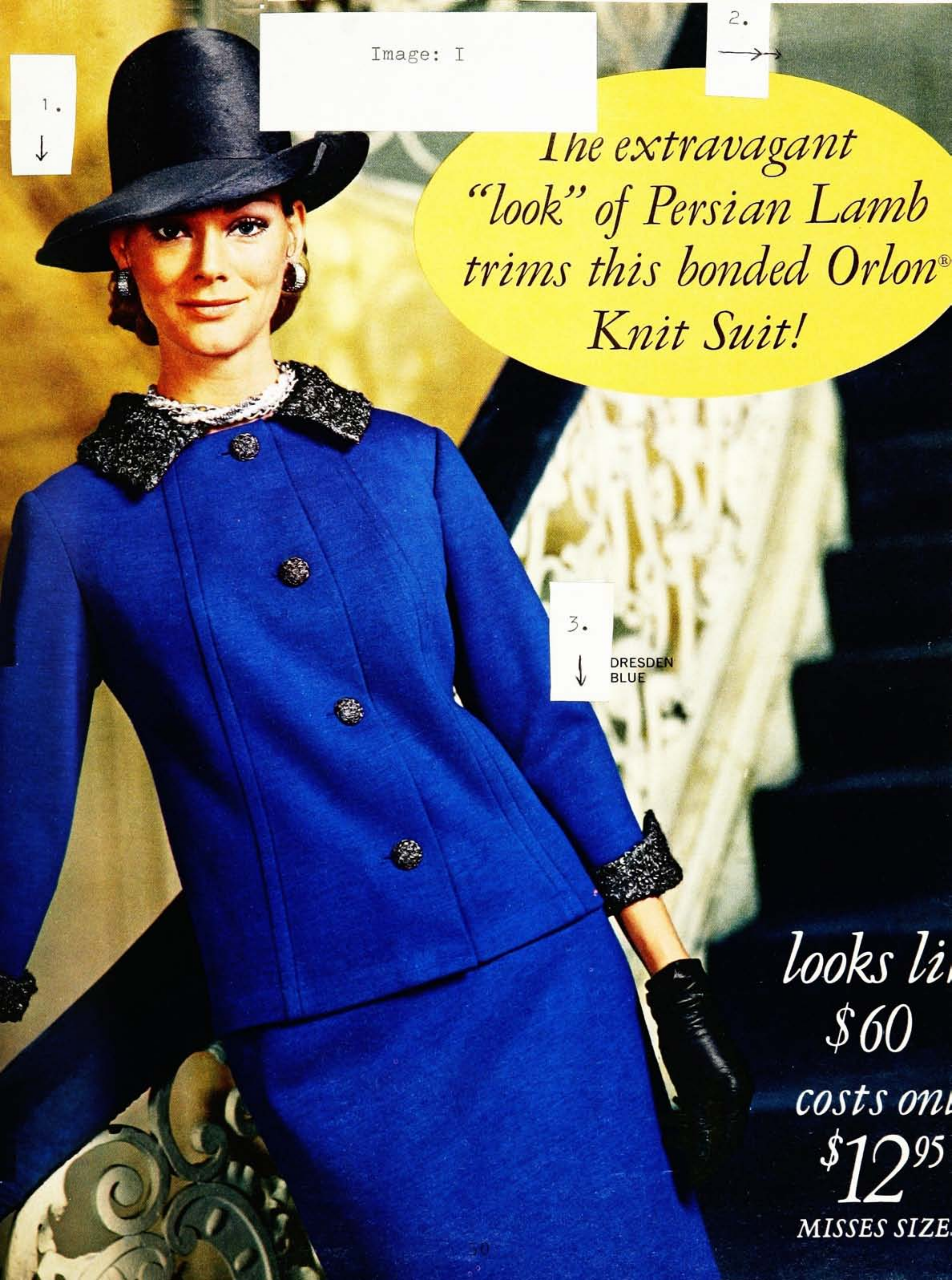
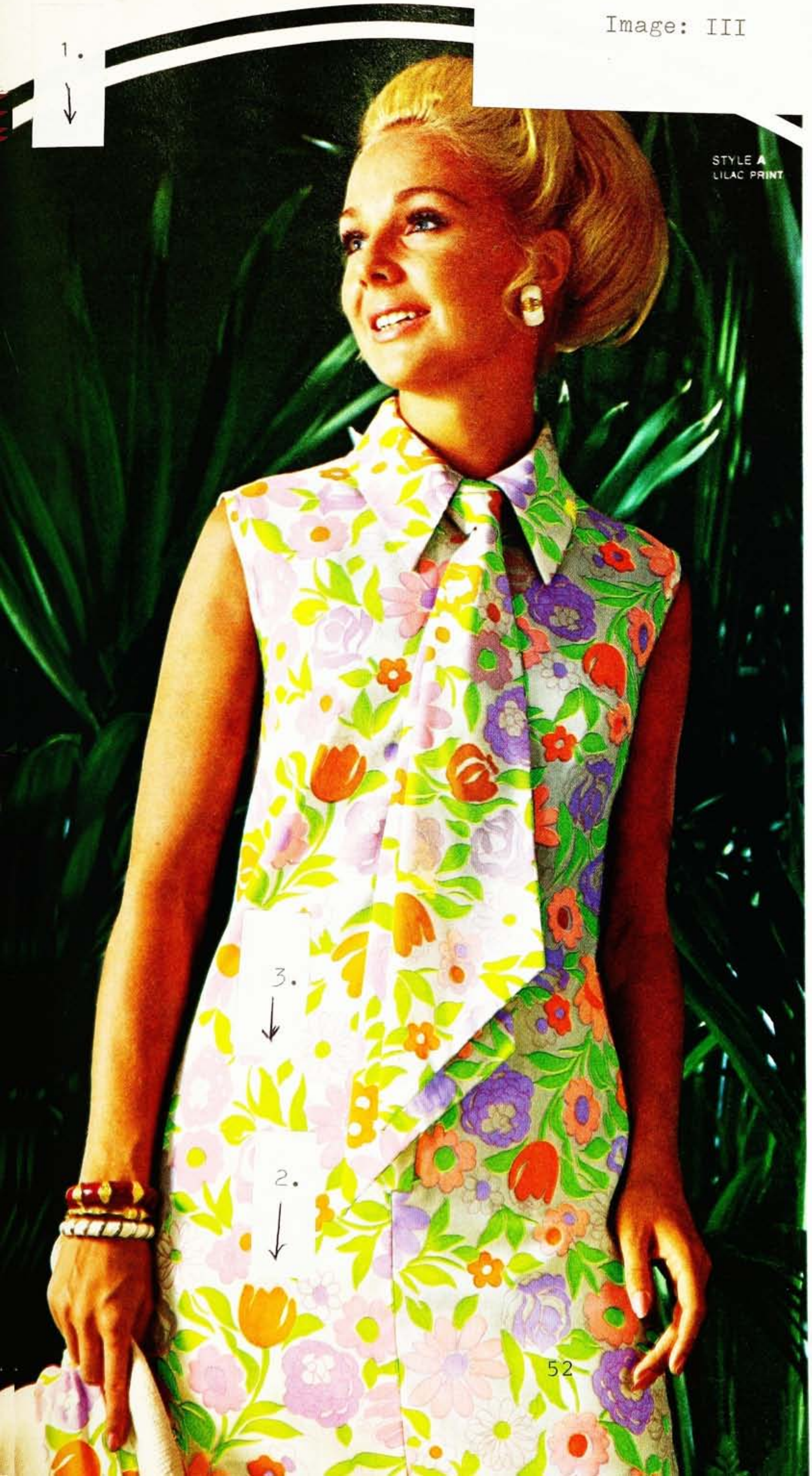


Image: I
1. ↓
2. →
The extravagant "look" of Persian Lamb trims this bonded Orlon® Knit Suit!
3. ↓
DRESDEN BLUE
looks li
$60
costs onl
$12.95
MISSES SIZE


Image: II
1.
2.
3.
Exciting
Blouse-n-Jumper
Go-Togethers!
Fashion

Image: III



Permaner Press

FORTREL® and AVRIL®

Shirtw Dre Specta

The fresh beauty of a spri
exciting Permanent Press
—so right for the new care
fashion this season! The st
50% Fortrel* polyester a
rayon makes these Perma
waist Classics a joy foreve
them in the wash and tum
come out crisp, fresh, eve
ironing, not even a touch
there, everywhere—you'll
turning compliments galo
freshest-staying Shirtwais
could wish for. Pick your
fabulous little-priced $20
now! We can promise no
when these are gone. Bett

Image: IV

We'll gladly send the Suit of your choice to see and wear a full week free! If it doesn't thrill you beyond your fondest expectations, simply return it and owe nothing. But don't wait! This fleeting, fantastic fashion find won't last long, and we can promise NO MORE! Better mail your Free Trial order form TODAY, hadn't you?

APPENDIX E

SAMPLE DATA COLLECTION SHEET

Image: Location:

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F													
C													
K													
A													
H													
J													
L													
B													
D													
G													

APPENDIX F

DEFINITION OF CORRELATION COEFFICIENT

For a set of given data points $\{(Xi, Yi)\ i = 1, 2, \ldots N\}$, the correlation coefficient is defined as follows:

$$\text{Correlation Coefficient } r = \frac{Sxy}{Sx\ Sy}$$

Where Sx and Sy are standard deviation:

$$Sx \sqrt{\frac{\Sigma xi^2 - (\Sigma xi)^2/n}{n-1}}$$

$$Sy \sqrt{\frac{\Sigma yi^2 - (\Sigma yi)^2/n}{n-1}}$$

Note: $-1 \leq r \leq 1$

APPENDIX G

COLLECTED AND TABULATED DATA

Image: I   Location: 1

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	4	2	5	5	3	2	10	3	1	2.7	3.9	3	1
C	11	11	12	20	26	25	20	13	18	5.9	17.3	13	13
K	17	11	20	20	25	26	30	26	18	6.1	21.4	14	16
A	20	11	15	12	27	28	32	17	25	7.9	20.8	11	10
H	25	34	18	26	26	32	20	20	10	7.4	23.4	10	28
J	30	34	24	26	33	38	32	28	31	4.3	30.7	13	28
L	36	21	22	31	35	28	32	23	40	6.7	29.8	12	16
B	37	34	28	43	31	44	32	38	48	6.7	37.2	21	20
D	43	48	34	45	45	46	32	44	48	5.8	42.8	12	28
G	46	48	48	49	50	48	48	47	48	1.2	48.0	44	44

$r_{\Delta E} = .74$

$r_{\Delta D} = .86$

Image: I Location: 2

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	6	2	3	10	4	4	2	3	2	2.6	4.0	9	3
C	14	11	8	20	28	27	30	17	32	8.8	20.8	15	14
K	26	11	24	20	28	28	22	33	10	7.8	22.4	18	20
A	16	11	10	20	28	27	30	20	32	8.2	21.6	10	10
H	24	22	27	26	30	25	22	28	20	3.2	24.9	41	44
J	31	22	33	38	36	37	32	35	48	6.9	34.7	30	38
L	38	48	28	38	45	31	32	36	48	7.4	38.2	7	22
B	46	48	46	47	50	45	48	43	48	2.0	46.8	18	37
D	35	37	37	38	40	42	32	45	48	5.0	39.3	15	38
G	43	48	48	47	50	47	32	48	48	5.5	45.7	43	63

$r_{\Delta E} = .35$

$r_{\Delta D} = .77$

Image: I Location: 3

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	7	3	15	3	5	8	2	4	2	4.2	5.4	6	4
C	13	5	5	3	13	20	10	7	2	5.9	8.7	4	7
K	24	21	21	12	31	20	22	33	32	6.9	24.0	8	18
A	20	5	3	3	13	13	10	10	2	6.1	8.8	3	7
H	39	43	50	40	50	44	49	38	32	6.2	42.8	31	60
J	33	29	34	26	40	37	33	37	42	5.1	34.6	18	38
L	15	9	12	20	15	15	22	12	11	4.2	14.6	5	9
B	30	29	26	31	47	44	33	38	42	7.4	35.6	16	26
D	41	29	30	25	44	37	33	37	42	6.5	35.3	15	31
G	26	26	25	25	35	29	33	40	32	5.3	30.1	15	22

$r_{\Delta E} = .90$

$r_{\Delta D} = .92$

Image: II

Location: 1

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	13	2	16	10	3	4	1	2	1	5.7	5.8	4	6
C	7	2	13	4	3	8	21	5	10	5.9	8.1	1	3
K	25	10	10	20	34	25	32	37	32	9.9	25.0	4	23
A	10	2	2	4	3	8	10	5	10	3.5	6.0	1	5
H	20	5	24	14	30	15	21	22	32	8.3	20.3	10	41
J	36	20	44	24	36	38	32	41	49	9.2	35.6	10	34
L	33	5	38	14	27	37	21	26	21	10.8	24.7	6	24
B	40	32	42	30	43	44	32	47	49	6.9	39.9	10	41
D	33	20	47	24	38	38	49	43	49	10.6	37.9	9	51
G	28	5	20	10	30	17	21	25	21	8.0	19.7	7	30

$r_{\Delta E} = .82$

$r_{\Delta D} = .88$

Image: II Location: 2

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	5	2	6	5	4	6	2	5	2	1.9	4.1	2	1
C	12	2	12	5	12	12	22	15	11	6.0	11.4	15	11
K	27	30	32	25	30	33	34	42	32	5.1	31.9	15	27
A	10	2	11	5	8	12	10	12	2	4.3	8.0	6	13
H	43	25	25	20	29	28	34	34	21	7.8	28.8	25	52
J	32	35	36	25	37	39	34	45	50	7.7	37.0	27	48
L	15	8	32	14	17	15	10	27	25	7.0	17.1	1	10
B	37	30	48	33	41	42	34	48	50	7.8	40.3	29	47
D	45	30	34	25	40	37	49	46	50	9.3	39.5	26	36
G	20	22	24	14	23	24	22	32	21	5.0	22.4	13	30

$r_{\Delta E} = .51$

$r_{\Delta D} = .87$

Image: II   Location: 3

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	7	3	11	13	6	3	2	3	2	4.2	5.5	5	4
C	15	3	15	20	12	15	21	12	2	7.0	12.9	13	18
K	17	11	8	26	21	30	33	31	11	10.0	20.9	15	25
A	11	3	14	20	12	15	21	13	2	7.0	12.4	15	17
H	25	18	22	30	24	25	33	28	22	4.8	25.4	17	44
J	23	22	25	30	29	30	33	35	32	4.8	28.8	18	48
L	32	8	48	48	36	33	33	34	50	13.6	35.8	17	29
B	35	22	30	35	37	37	33	46	50	8.7	36.0	20	46
D	38	35	37	39	40	37	33	45	50	5.6	39.3	21	43
G	42	35	27	48	43	40	50	49	50	8.3	42.6	42	51

$r_{\Delta E} = .77$

$r_{\Delta D} = .87$

Image: III Location: 1

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	10	1	10	2	13	5	1	3	1	4.7	5.1	5	5
C	30	48	43	32	40	37	32	44	47	6.8	39.2	34	30
K	28	48	38	32	42	48	32	42	31	7.5	37.9	31	25
A	29	48	45	32	40	48	32	44	47	7.6	40.6	32	27
H	42	21	11	22	31	32	32	30	31	8.8	28.0	17	33
J	35	40	34	32	40	37	30	37	31	3.7	35.1	27	36
L	37	48	20	22	40	44	30	36	47	10.2	36.0	26	55
B	44	48	48	49	45	48	50	47	50	2.1	47.7	49	45
D	15	24	6	8	26	20	20	20	20	6.8	17.7	11	13
G	50	29	30	49	50	44	32	39	47	8.8	41.1	27	42

$r_{\Delta E} = .93$

$r_{\Delta D} = .77$

Image: III   Location: 2

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	5	2	7	3	2	2	1	3	2	1.9	3.0	4	1
C		10	4	10	10	20	21	32	12	9.0	14.9	26	22
K		22	22	17	33	27	32	29	22	5.6	25.5	28	32
A		5	13	10	10	17	21	32	12	8.4	15.0	26	17
H		22	32	20	36	27	32	25	33	5.8	28.4	35	48
J		22	37	20	40	31	32	28	33	6.9	30.4	34	46
L		5	27	10	21	8	10	22	12	7.8	14.4	15	22
B		22	29	20	38	31	48	32	33	8.9	31.6	31	43
D		22	25	20	35	24	32	5	33	9.6	24.5	23	53
G		10	17	17	28	24	32	13	26	7.8	20.9	19	35

$r_{\Delta E} = .86$

$r_{\Delta D} = .92$

Image: III Location: 3

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F		1	3	5	8	2	1	3	2	2.4	2.9	2	1
C		22	19	15	28	27	33	12	20	7.0	22.0	34	45
K		22	29	8	27	27	33	27	31	7.8	25.5	32	42
A		22	34	15	25	32	33	12	39	9.7	26.5	13	61
H		22	36	30	33	20	48	30	31	7.4	32.5	31	58
J		11	22	23	23	27	33	33	20	7.2	24	33	42
L		16	25	8	25	20	21	10	2	8.4	15.9	18	33
B		22	30	13	27	32	33	28	39	7.8	28.0	40	59
D		4	28	5	12	8	11	30	11	9.9	13.6	15	23
G		11	33	30	33	32	21	25	39	8.7	28.0	20	42

$r_{\Delta E} = .71$

$r_{\Delta D} = .94$

Image: IV Location: 1

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	3	1	7	2	6	3	10	3	1	2.8	4.0	3	2
C	13	10	13	21	29	15	20	20	27	6.5	18.7	19	20
K	14	20	18	27	33	29	20	32	27	6.7	24.4	21	21
A	10	10	10	21	29	13	20	18	20	6.5	16.7	16	17
H	28	32	32	31	45	37	31	33	32	4.9	33.4	25	41
J	30	32	20	27	33	30	31	33	32	4.1	29.8	25	38
L	9	10	9	21	29	10	20	17	10	7.1	15.0	11	10
B	38	32	25	31	33	37	31	45	48	7.2	35.6	27	37
D	47	46	48	47	50	47	48	46	48	1.2	47.4	32	31
G	43	46	30	40	45	43	31	47	48	6.6	41.4	28	36

$r_{\Delta E} = .97$

$r_{\Delta D} = .86$

Image: IV Location: 1

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	3	1	7	2	6	3	10	3	1	2.8	4.0	3	2
C	13	10	13	21	29	15	20	20	27	6.5	18.7	19	20
K	14	20	18	27	33	29	20	32	27	6.7	24.4	21	21
A	10	10	10	21	29	13	20	18	20	6.5	16.7	16	17
H	28	32	32	31	45	37	31	33	32	4.9	33.4	25	41
J	30	32	20	27	33	30	31	33	32	4.1	29.8	25	38
L	9	10	9	21	29	10	20	17	10	7.1	15.0	11	10
B	38	32	25	31	33	37	31	45	48	7.1	35.6	27	37
D	47	46	48	47	50	47	48	46	48	1.1	47.4	32	31
G	43	46	30	40	45	43	31	47	48	6.6	41.4	28	36

$r_{\Delta E} = .97$

$r_{\Delta D} = .86$

Image: IV Location: 2

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	7	2	3	2	2	3	11	5	1	3.2	4.0	3	2
C	30	33	33	20	44	26	32	33	33	6.4	31.6	23	16
K	35	33	35	20	34	35	32	35	21	6.0	30.9	19	24
A	27	33	26	20	45	26	32	33	33	7.0	30.6	21	15
H	29	48	29	29	48	27	32	38	27	8.6	34.1	21	44
J	44	48	42	35	47	42	32	42	50	5.8	42.4	26	44
L	24	22	15	17	30	30	22	21	21	6.0	22.4	13	9
B	47	48	46	40	50	45	48	49	50	3.1	47.0	35	41
D	40	48	48	40	47	45	48	45	50	3.7	45.7	18	17
G	46	48	40	48	46	49	48	46	50	2.9	46.8	33	41

$r_{\Delta E} = .88$

$r_{\Delta D} = .74$

Image: IV Location: 3

	M.P.	S.A.	O.S.	B.A.	I.F.	R.H.	C.S.	D.J.	B.C.	S	$\overline{X}$	ΔE	ΔD
F	7	2	3	3	2	2	2	2	2	1.6	2.8	4	2
C	20	25	22	5	22	15	33	12	33	9.2	20.8	20	16
K	25	9	18	12	29	27	33	22	27	8.0	22.4	21	23
A	19	25	14	5	25	14	33	12	33	9.7	20.0	20	33
H	30	19	17	20	34	41	33	37	33	8.6	29.3	24	44
J	34	19	26	20	34	32	33	37	33	8.0	29.7	24	41
L	11	25	6	5	22	9	22	12	11	7.4	13.7	14	11
B	37	19	26	20	35	37	33	44	33	8.3	31.6	26	38
D	40	33	29	25	39	43	49	47	49	8.8	39.3	16	20
G	45	33	45	35	45	48	49	48	49	6.0	44.1	28	41

$r_{\Delta E} = .78$

$r_{\Delta D} = .71$